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A framework for reviewing the trade-offs between, renewable energy, food, feed and wood production at a local level

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ABSTRACT

High fuel prices and concerns about energy security and anthropogenic climate change are encouraging a transition towards a low carbon economy. Although energy policy is typically set at a national level, tools are needed for people to engage with energy policy at regional and local levels, and to guide decisions regarding land use, distributed generation and energy supply and demand. The aim of this paper is to develop a per-capita approach to renewable energy demand and supply within a landscape and to illustrate the key trade-offs between renewable energy, food, (animal) feed and wood production. The chosen case study area (16,000 ha) of Marston Vale, England is anticipated to have a population density midway between that for England and the UK. The daily per capita demand for energy for heat (31 kWh), transport (34 kWh) and electricity (15 kWh) when combined (80 kWh) was seven-fold higher than the combined demand for food (2 kWh), animal feed (6 kWh), and wood (4 kWh). Using described algorithms, the combined potential energy supply from domestic wind and photovoltaic panels, solar heating, ground-source heat, and municipal waste was limited (<10 kWh p^{-1} d^{-1}). Additional electricity could be generated from landfill gas and commercial wind turbines, but these have temporal implications. Using a geographical information system and the Yield-SAFE tree and crop yield model, the capacity to supply bioethanol, biodiesel, and biomass, food, feed and wood was calculated and illustrated for three land-use scenarios. These scenarios highlight the limits on meeting energy demands for transport (33%) and heat (53%), even if all of the arable and grassland area was planted to a high yielding crop like wheat. The described framework therefore highlights the major constraints faced in meeting current UK energy demands from land-based renewable energy and the stark choices faced by decision makers.

Contents

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1. Introduction

The United Kingdom (UK), as is the case for many countries, faces an energy challenge. Reduced availability of domestic fossil fuels, rising fossil fuel prices and the need to constrain greenhouse gas emissions means that the country must reduce energy consumption, import more energy, and/or develop new domestic energy sources with lower carbon footprints such as renewable energy.

In 2000, the UK Government's renewable energy policy [1] was to increase the contribution of electricity supplied from renewables to 5% by the end of 2003 and to 10% in 2010, assuming acceptable consumer costs. More recently, the 2009 renewable energy directives set a target for the UK to achieve 15% of its energy consumption from renewable sources by 2020 [2]. It is considered that this could be achieved by supplying 31% of the electricity demand, 10% of the transport demand and 12% of the heat demand [2]. In 2008, only about 2.3% of the delivered energy supply in the UK came from renewable sources [3]. The proportion of electricity from renewable sources was 5.5%, and the proportions of transport fuel and energy for other use including heat were about 1.4% each.

The development of renewable energy sources, especially the cultivation of energy crops, also has the potential to affect our national and global ecosystems and the services they provide. These benefits provided by ecosystems have been termed "ecosystem services" [4]. In some of the literature on ecosystem services, the focus is on semi-natural and natural systems [5], however elsewhere the focus is on the full range of ecosystems including agricultural and urban systems [4]. Within the context of the UK, virtually all ecosystems are heavily affected by mankind and therefore this paper uses the wider interpretation.

Authors have generally found it useful to categorise the services that humans get from ecosystems into four or five functional groups which typically include production, regulating and cultural components (Table 1). In addition to these groups De Groot [5] highlights a "habitat" and a "carrier" category. He defines the carrier function as the provision of a "space and suitable substrate to support infrastructure associated with human activities" and gives examples of the capture of wind and solar energy and the food production from cultivated land. However as mentioned previously, in the context of the UK, it is useful to view agriculture as being an ecosystem in its own right, and therefore this paper considers agricultural food production to be a production rather than a carrier service.

The research described in this paper was undertaken as part of a one year pilot project entitled "Energyscapes and Ecosystems Services" which sought to describe and explain the effect of different renewable energy systems on ecosystem services. The aim of this paper is to develop a per capita approach to renewable energy demand and supply within a predefined geographical area and, through the use of scenarios, to illustrate some of the key trade-offs and synergies between the production of renewable energy (electricity, transport, and heat) and the production of three other commodities, namely, food, animal feed and wood.

2. Methodology

2.1. Case study area

The Marston Vale comprises 16,094 ha to south and west of the county town of Bedford in southern England (Fig. 1). The area is bordered by the Greensand Ridge in the south and a motorway (the M1) in the south-west. Census data from 2001 indicates there were 10,646 households in the area, and assuming a mean of 2.4 people per household in 2009 [7], this equates to 25,550 people. The area is also part of a "growth area" and therefore there has been government investment in transport infrastructure to support housing development, including a new town, called Wixams, close to the centre of the area. In total it is estimated that development consent has been given for another 10,036 houses, which assuming the same number of people per household, would double the population to 49,637. This higher population is equivalent of 0.32 ha per person (3.1 people per ha). This is intermediate between the mean values for England (3.9 people per ha) and the UK (2.5 people per ha), but higher than mean values for the European Union (1.2 people per ha) or the world (0.46 people per ha).

2.2. Mapping land use

A digital map of the area was developed within a geographical information system ARCGIS (ESRI Inc, 2009) using aerial photographs from June 2009 available from Google Earth (Google, 2010). The field digitisation was performed at a basic scale of 1:5000 with a minimum mapping unit of 0.5 ha. The land use within each polygon in the GIS was also coded into one of 17 categories which fall into three classes (Table 2, Fig. 1a).

Using current land use as a foundation, an additional category of "Consented development" was also created. The existing polygons in the same areas were then sub-divided into areas where development was consented or not (Fig. 1b). Lastly in order to facilitate

Table 1
Ecosystem services can be categorised into five functional groups as described by De Groot et al. [6] and De Groot [5]. The focus of this paper is on the production and carrier functions.

Functional group	Description	Examples services
Production	Production of carbohydrate structures	Food, animal feed, energy resources, genetic material
Carrier	Providing a space and substrate for human infrastructure	Housing, transport, non-biomass energy supply, waste storage
Regulating	Bio-geochemical cycles and biospheric processes	Carbon dioxide, oxygen, climate, water and soil regulation
Cultural	Providing opportunities for cognitive development	Recreational and cultural spaces
Habitat	Providing habitat for wild plants and animals	Designated conservation areas

statistical analysis, the land use polygons were expressed as values within a grid of 100 m × 100 m pixels. Because only those squares which lay completely within the Marston Vale were selected, the area of pixel-based data (15,565 ha) was 3% smaller than the area of the Vale (16,094 ha). Using the pixel-based data, agriculture occupied about 71% of the total area (Table 3) compared to a values of 75% for England and 77% for the UK [8].

The principal arable crops were wheat (27%) and oilseed rape (OSR) (9%), with smaller areas of barley (3%) and other crops including field beans and peas (7%); a significant area (6%) was also considered "fallow". Grassland occupied 18% of the area, which is less than the average value for England (39%) and the UK (52%), as a result of the high proportion of arable land. The other principal land use categories were woodlands (8%), urban (8%), other (9%),

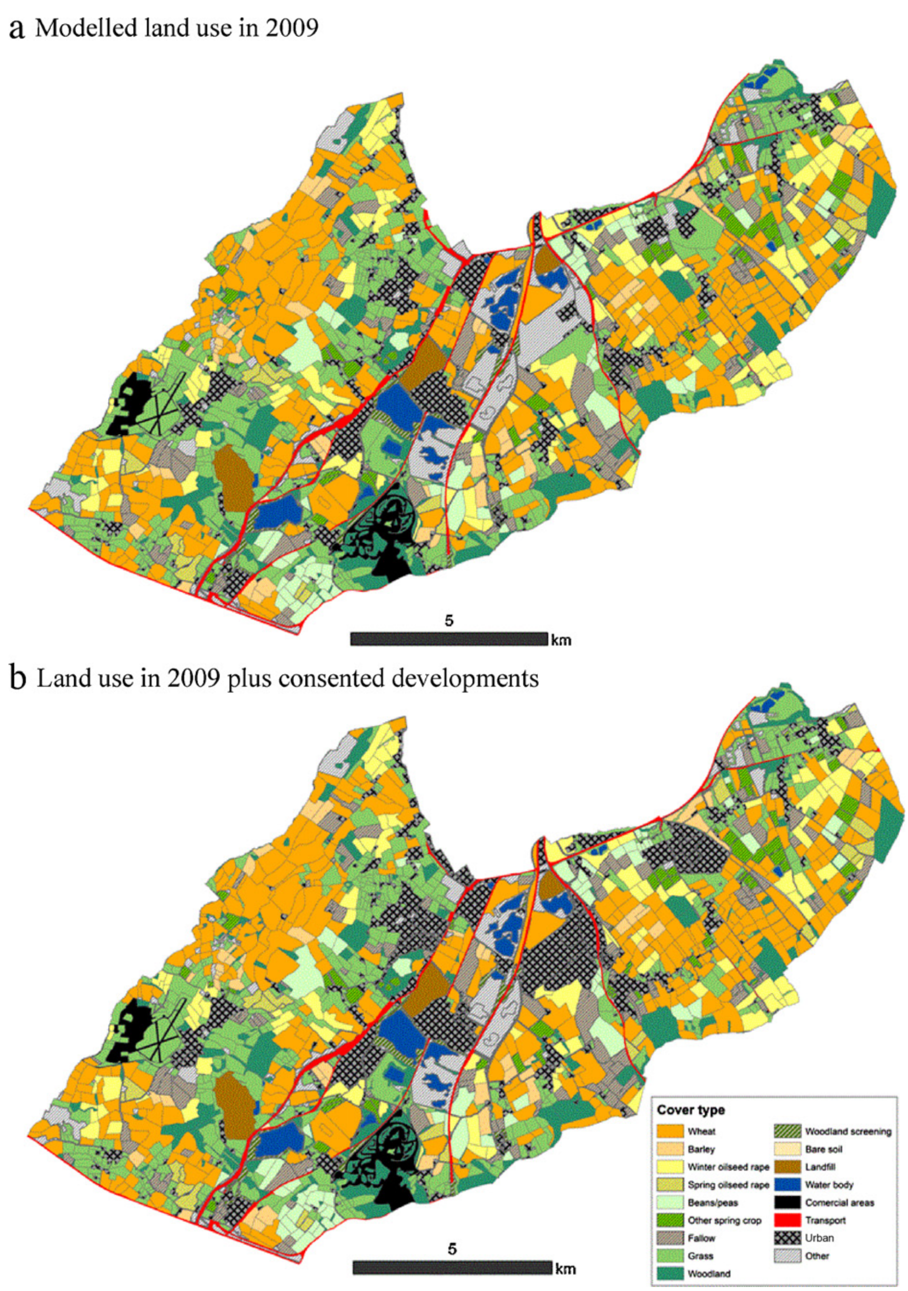


Fig. 1. Modelled land use within the Marston Vale in 2009 (a) without and (b) with consented development.

Table 2
Categories of land use used within the geographical information system.

Class	Categories
Agricultural land	Wheat, winter oilseed rape, spring oilseed rape, barley, beans/peas, other spring crop, fallow, bare soil, grass
Woodland	Woodland, woodland screening
Other	Water, urban, transport infrastructure, commercial area, landfill, other

water (2%) and land-fill (2%) (Table 3). The inclusion of consented development is predicted to increase the area allocated to urban land from 8 to 12%, resulting in a reduction of land in the grassland and other categories.

2.3. Determining energy demand

A key issue in energy-environment studies is a choice of unit that people can relate to. Whilst national statistics may use million tonnes of oil equivalent or Gigajoules, it is arguable that a more "human-sized unit" [9] is the number of kilowatt hours per day per person ($kWh\,d^{-1}\,p^{-1}$). One kWh is equivalent to 3600 kJ. In 2002, the average world citizen consumed the equivalent of 56 $kWh\,d^{-1}$ [10]. In 2008, the primary annual UK energy use was 117 $kWh\,d^{-1}\,p^{-1}$, approximately twice the global average [3]. Because the conversion of energy sources like coal and gas to electricity is typically about 30% efficient, the delivered energy is substantially lower. In 2008, the mean delivered energy per person in the UK was equivalent to 80 $kWh\,d^{-1}$ [3] (Table 4).

Within Marston Vale, domestic energy use (electricity, transport, and heat and other) was calculated using estimates of the number of households per ward, and the mean household energy consumption for the two local authorities covering the area [11] (Table 4). Electricity and heat energy use within commercial buildings was derived from the plan area of the 88 largest warehouses and offices in the Marston Vale and average benchmark values for fossil fuel and electricity use per unit area of the commercial buildings [12]. The energy related to freight transport in the Vale was derived from freight transport energy use for the two local authority areas on a proportional area basis. The energy use associated with arable and grassland production systems were derived from land use data, agricultural statistics, and life cycle assessment values reported by Williams et al. [13]. The derived value of 81 $kWh\,p^{-1}\,d^{-1}$ for the Vale is similar to the mean value of 80 $kWh\,p^{-1}\,d^{-1}$ for the UK (Table 4).

Using the national values, the current demand was established for electricity (15 $kWh\,p^{-1}\,d^{-1}$), transport (34 $kWh\,p^{-1}\,d^{-1}$) and heat and other uses (31 $kWh\,p^{-1}\,d^{-1}$). As indicated earlier, the UK is seeking to achieve 15% of its energy consumption from renewable sources by 2020 [2], which would be equivalent to 31% of the electricity demand, 10% of the transport demand and 12% of the heat demand [2]. Applied to UK energy use in 2008, this is equivalent to 4.6 $kWh\,p^{-1}\,d^{-1}$ of electricity, 3.4 $kWh\,p^{-1}\,d^{-1}$ of transport fuel, and 3.7 $kWh\,p^{-1}\,d^{-1}$ of heat.

2.4. Food demand

In the UK, the mean level of food energy purchased (including eating out and alcohol), for people aged above seven years is about 2275 kcal per person per day [15] (Table 5). Food energy requirements for humans equate conceptually most closely with estimates of metabolisable energy [16], which is the energy that can be delivered by food minus the energy used for digestion. This daily value, which is equivalent to 2.65 kWh per person, included household wastage which was assumed to be about 10%. Pimental and Pimental [17] in the United States considered a daily diet equivalent to 3533 kcal (4.1 kWh), which was considered to be 1000 kcal above what was needed. Alexandratos et al. [18] using values from national food accounts rather than household usage, estimated that daily food use per person in industrial countries was equivalent to 3446 kcal (4.0 kWh) in 1999–2001.

The mean daily UK consumption of food products of 2.65 kWh per person comprises 1.93 kWh (73%) which is plant-based and 0.72 kWh (27%) which is animal-based [15]. Values for the energy density of milk, eggs and meat, and conversion rates of grass and grain for milk, egg and meat production were derived from Williams et al. [13]. Using these values, the production of the typical range of animal products consumed in the UK requires 2.84 $kWh\,p^{-1}\,d^{-1}$ of grass and 2.80 $kWh\,p^{-1}\,d^{-1}$ of other animal feed (5.64 $kWh\,p^{-1}\,d^{-1}$ in total) (Fig. 2). This represents three-quarters of a combined food and feed requirement of 7.57 $kWh\,p^{-1}\,d^{-1}$.

Table 3
Estimated land use (ha) in Marston Vale in 2009 (without and with consented development) based on a matrix of 100 m × 100 m pixels. Values in brackets are percentages (%).

	Current		Current plus consented	
Wheat	4206	(26.8)	4141	(26.4)
Barley	455	(2.9)	456	(2.9)
Oilseed rape[a]	1491	(9.5)	1481	(9.5)
Other crop[b]	1104	(7.0)	1099	(7.0)
Fallow[c]	994	(6.3)	974	(6.2)
Grass	2821	(18.0)	2599	(16.6)
Sub-total Agriculture	11,071	(70.7)	10,750	(68.6)
Woodland[d]	1312	(8.4)	1281	(8.2)
Urban	1266	(8.1)	1861	(11.9)
Landfill	236	(1.5)	236	(1.5)
Water	352	(2.2)	352	(2.2)
Other[e]	1428	(9.1)	1185	(7.6)
	15,665		15,665	

[a] Oilseed rape is the sum of winter and spring oilseed rape.
[b] Other crop is the sum of beans/peas and other spring crops.
[c] Fallow is the sum of fallow and bare soil.
[d] Woodland is the sum of woodland and woodland screening.
[e] Other includes commercial areas, transport infrastructure and other non-cultivable areas.

Table 4
Estimates of current energy use within Marston Vale and the UK. The UK values also include illustrative renewable energy targets for 2020.

Area	Source	Electricity	Transport	Heat[c]	Total
Marston Vale	Domestic (GWh)	53	154	172	379
	Commercial (GWh)[a]	75	168	97	340
	Agricultural (GWh)[b]	12	13	12	35
	Total (GWh)	140	335	281	754
	Total ($kWh\,p^{-1}\,d^{-1}$)	15	36	30	81
UK [14]	Total ($kWh\,p^{-1}\,d^{-1}$)[c]	15	34	31	80
	Assumed proportion of renewables	0.31	0.10	0.12	0.15
	Renewable target ($kWh\,p^{-1}\,d^{-1}$)	4.6	3.4	3.7	11.7

[a] Commercial electricity and heat use based on area of warehouses (356,500 m^2) and offices (179,400 m^2). Annual mean fossil fuel and electricity use in warehousing estimated as 133 $kWh\,m^{-2}$ and 32 $kWh\,m^{-2}$ respectively [12]. Annual mean fossil fuel and electricity use in offices (assumed double storey) at 138 $kWh\,m^{-2}$ and 177 $kWh\,m^{-2}$ respectively [12].
[b] Estimate of 35 GWh for arable and grazing systems in the Marston Vale in 2009 was assumed to be split equally between electricity, transport and heat.
[c] Total delivered energy consumption in the UK in 2009 was 154.3 million tonnes of oil equivalent. Assuming that one tonne of oil is equivalent to 11,630 kWh and that the population of the UK is 61.4 million [7], mean energy use is 80 $kWh\,p^{-1}\,d^{-1}$. Of this 29.4 million tonnes of oil was used for electricity (15 $kWh\,p^{-1}\,d^{-1}$), 64.9 million tonnes was for transport (34 $kWh\,p^{-1}\,d^{-1}$), and the difference was attributed to heat and other forms of energy (31 $kWh\,p^{-1}\,d^{-1}$).

Table 5
Estimate of food energy purchase by UK households (>7 years old) [15], and the derived estimates of the animal feed required using values from Williams et al. [13].

Product	Human food energy purchase ($kWh\,p^{-1}\,d^{-1}$)	Energy density of food ($MJ\,kg^{-1}$)	Grass input/food output ($kg\,kg^{-1}$)	Animal grass intake[a] ($kWh\,p^{-1}\,d^{-1}$)	Crop input/grain output ($kg\,kg^{-1}$)	Animal crop intake[b] ($kWh\,p^{-1}\,d^{-1}$)
Plant-products	1.93					
Milk	0.30	2.8	0.9	0.86	0.5	0.77
Poultry	0.16	8.7			3.1	0.76
Pig meat	0.08	9.2			4.4	0.54
Beef	0.07	9.0	14.5	1.08	4.3	0.47
Lamb	0.03	10.5	33.4	0.90	2.9	0.12
Eggs	0.02	6.3			3.1	0.14
Fish	0.04					
Animal-products	0.72			2.84		2.80
Total	2.65					

[a] Energy value of grass (15% moisture content) assumed to be 9 $MJ\,kg^{-1}$.
[b] Energy content of crop input (16% moisture content) assumed to be 13.3 $MJ\,kg^{-1}$.

2.5. Wood demand

In 2005, the apparent consumption of wood in the UK, primarily in the form of paper, was 44.7 million m^3 wood raw material equivalent underbark [19]. Assuming a UK population of 61.4 million in 2008 [7], this is equivalent to 0.728 m^3 of wood per person per year. Assuming a mean dry density for temperate wood of 460 $kg\,m^{-3}$ [20], marketable timber with a moisture content (wet basis) of 30% would have a density of 657 $kg\,m^{-3}$. Assuming that wood with a moisture content of 30% has an energy value of 12.1 $MJ\,kg^{-1}$ [21], this is equivalent to 4.4 $kWh\,p^{-1}\,d^{-1}$ (Fig. 2).

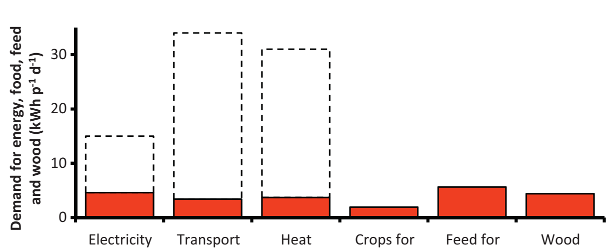


Fig. 2. Total (dotted area) and the 2020 renewable target (shaded area) demand for electricity, transport fuels, and heat, and the demand (shaded area) for food (crops for human consumption), animal feed (crops and grass), and wood.

2.6. Collation of energy data

The potential supply of energy within Marston Vale was determined using algorithms combining spatial information with values determined from the literature. The assumed energy from solar panels on domestic buildings was based on the number of households, an estimate of the area per house, and the assumption that one-eighth of the roof area could be used for solar panel installation (Table 6). A similar estimate was derived for commercial buildings. Estimates for electricity energy from wind were based on the potential number of wind turbine sites beyond specific buffers around urban, commercial and woodland areas, and estimates of electricity output for a specific type of wind turbine (Table 7).

It was assumed that domestic solar heating panels would be designed to meet the hot water requirement in July (Table 8). For ground-source heating, the assumption was that ground-source heating could supply 100% of the space heating in new domestic buildings (Table 8). Estimates were also made of the energy that could be generated from municipal waste (Table 9). There was no significant source of hydro-electricity in the area. At present the only significant renewable energy source used in the Vale is the use of landfill gas to generate electricity. The active landfill sites at Brogborough, L'Field Stewartby, and Elstow generated 254 GWh of electricity over 12 months in 2009/2010 [34] (Table 10). However this energy is being generated from waste obtained from an area extending beyond the Marston Vale, and the level of landfill gas will decline over time. Therefore although the resource is important in the short- to medium-term it is not a long-term renewable energy source.

Table 6
Estimated potential energy production from solar photovoltaics (PV) in the Marston Vale.

Energy source	Output	Properties	Mean roof area (m^2)	Proportion of roof used	Annual yield ($kWh\,m^{-2}$)	Energy (GWh)	Energy ($kWh\,p^{-1}\,d^{-1}$)[a]
Domestic PV	Electricity	20,682	98[b]	0.125	117[c]	29.6	1.6
Existing commercial PV	Electricity	88[d]	6092[c]	0.125	117[c]	7.8	0.4

[a] Per capita values are based on a population of 49,637.
[b] Typical areas per domestic houses in the ward areas of Great Barford, Marston and Eastcotts calculated using Department of Communities and Local Government [22] values are about 98 m^2. Using an eighth of the area means a mean panel size of 12 m^2.
[c] Highest yield recorded in the 2003 publication by Jardine and Lane [23] in Oxford.
[d] The plan area of the 88 largest commercial buildings in 2009 were calculated from aerial photographs using the geographic information system.

Table 7
Estimated potential energy production from wind turbines in the Marston Vale.

Energy source	Output	Number of turbines	Annual energy output per turbine (kWh)	Energy (GWh)	Energy[a] ($kWh\,p^{-1}\,d^{-1}$)
Large wind turbine (2 MW)	Electricity	98[b]	3,897,000[c]	381.9	21.1
Domestic pole-mounted	Electricity	176[d]	11,578[e]	2.0	0.1

[a] Per capita values are based on a population of 49,637.
[b] Estimate of number of turbines assuming a buffer around all current and consented settlements (800 m buffer), commercial areas (500 m), and woodlands (500 m) and excluding water bodies and areas where the slope was greater than 10%. A minimum spacing of 335 m of five times a blade diameter of 67 m was assumed [24].
[c] National Energy Foundation [25] quoted by ENTEC [26] estimated that an Enercon E70 (2 MW) wind turbine with a hub height of 64 m would generate 3,897,000 kWh per year (capacity factor of 22%) assuming a wind speed of 6.1 $m\,s^{-1}$.
[d] The Energy Savings Trust [27] recommends that wind turbines should only be located in areas where the windspeed is at least 5 $m\,s^{-1}$ using the MCS adjusted NOABL tool. Within the Marston Vale study area, a wind speed of 5 $m\,s^{-1}$ or more will only occur in rural areas [28]. The proportion of houses in rural areas is assumed to be 3.3% [24] of the existing 10,656 dwellings (351 houses). For the purposes of this exercise it is assumed that half of the rural houses could use a pole-mounted turbine (176).
[e] Annual mean output for a pole-mounted turbine (non-farm based) is 11,578 kWh [27].

Table 8
Estimated potential energy production from solar heating panels and ground-source heat pumps in the Marston Vale.

Energy source	Output	Households	Annual water heating per house (kWh)	Mean floor area per house (m^2)	Annual mean space heating ($kWh\,m^{-2}$)	Heating requirement (GWh)	Energy ($kWh\,p^{-1}\,d^{-1}$)[a]
Domestic solar heating panels	Water heating	20,692	1273[b]			26.3	1.4
Ground source heat pumps	Space heating	10,036		91.2[c]	128.5[c]	117.8	6.5
	Electricity						−1.8

[a] Per capita values are based on a population of 49,637.
[b] Mean level of domestic hot water heating is 16.8 $MJ\,d^{-1}$ [28], or 1703 kWh per year. In July the mean hot water user per household is 100 L and the average temperature rise is 30 °C [29], so assuming a specific heat capacity of water of 4.2 $kJ\,kg^{-1}\,K^{-1}$, the annual water heating per house would be 1273 kWh. As a collector can annually capture about 500 $kWh\,m^{-2}\,a^{-1}$ [30], this would require 2.5 m^2 of collector.
[c] Mean space heating required for a GB house in 2006 = 11,716 kWh [31], and mean total usable floor area of a dwelling in England in 2008 was 91.2 m^2 [32], therefore average annual space heating requirement is 128.5 $kWh\,m^{-2}$. However it is assumed that a ground-source heat pump has an output of 3.5 units of heat for 1 unit of electrical input [30].

Table 9
Estimated potential energy production from municipal waste in the Marston Vale.

Energy source	Output	Quantity of waste ($t\,person^{-1}\,year^{-1}$)	Output ($kWh\,t^{-1}$)	Energy (GWh)	Energy ($kWh\,p^{-1}\,d^{-1}$)[a]
Municipal waste	Electricity	0.53[b]	735[c]	19.4	1.1
	Heat	0.53	402[d]	10.5	0.6

[a] Per capita values are based on a population of 49,637.
[b] Central Bedfordshire produces 136,000 tonnes of waste from 255,000 people.
[c] Covanta Energy Ltd [33].
[d] This is below the potential, but is considered usable [33].

Table 10
Electricity production in the Marston Vale from landfill gas for 2009–2010 [34].

Output	Site	Area (ha)	Electricity capacity (MW)	Energy (GWh)	Energy ($kWh\,p^{-1}\,d^{-1}$)[a]
Electricity	Brogborough	125	28.7	191.0	
	Stewartby	78	12.5	58.0	
	Elstow	32	1.8	4.6	
	Sub-total	261	43.0	253.6	14.0

[a] Per capita values are based on a population of 49,637.

Table 11
Summary of the mean yield of biomass crops and the energy yield for food, feed, wood, heat, electricity and fuel assuming current land use, and if all the agricultural area (10,750 ha) was allocated to that crop. Per capita values assume 49,637 people.

Crop and current area	Component and moisture content (wet basis)	Yield dry ($t\,ha^{-1}$)	Yield wet ($t\,ha^{-1}$)	Harvested proportion	Use	Energy yield ($MJ\,kg^{-1}$)[a]	Efficiency	Energy yield ($kWh\,ha^{-1}$)	Energy on current area ($kWh\,p^{-1}\,d^{-1}$)	Energy on 10,750 ha ($kWh\,p^{-1}\,d^{-1}$)
Wheat (4141 ha)	Grain (16%)	8.20	9.76	1.00	Food	13.3[b]	1.0	36,000	8.2	21.4
				1.00	*or* Heat	13.9[c]	0.8	30,100	6.9	17.9
	Ethanol (0%)			0.29	*or* Fuel *and*	26.7[d]	1.0	21,000	4.8	12.4
	Distiller grains (10%)			0.47	Feed	14.4[f]	1.0	18,400	4.2	10.9
	Straw (15%)	6.24	7.34	0.65	Feed	4.8[e]	1.0	6300	1.4	3.7
					or Heat	14.3[c]	0.8	15,100	3.5	9.0
Barley (456 ha)	Grain (16%)	6.29	7.49	1.00	Feed	12.4[a]	1.0	25,800	0.6	15.3
	Straw (15%)	7.38	8.68	0.65	Feed	6.2[e]	1.0	9700	0.2	5.8
					Heat	14.5[c]	0.8	18,200	0.5	10.8
Oilseed (1481 ha)	Rapeseed (15%)	3.33	3.92	1.00						
	Rapeseed oil (0%)			0.37	Food	37.2[d]	1.0	15,000	1.2	8.9
				0.35	Biodiesel	37.2[d]	1.0	14,200	1.2	8.4
	Rapemeal (15%)			0.55	Feed	10.1[a]	1.0	6000	0.5	3.6
				0.55	*or* Heat	14.1[d]	0.8	6700	0.5	4.0
	Straw (15%)	5.50	5.88	0.65	Heat	14.2[c]	0.8	12,000	1.0	7.1
Spring crop (1099 ha)	Pulse (12%)	3.49	3.97	1.00	Feed	13.8[a]	1.0	15,200	0.9	9.0
	Straw (15%)	6.48	7.62	0.65	Heat	14.2[c]	0.8	15,600	0.9	9.3
Grass (2598 ha)	Grass (15%)	7.14	8.40	0.65	Feed	9.0[e]	1.0	13,700	2.0	8.1
					or Heat	14.4[c]	0.8	17,500	2.5	10.4
Hardwood (1281 ha)	Timber (30%)	3.62	5.17	0.70	Timber	12.1[c]	1.0	12,200	0.9	7.2
					or Heat		0.8	9800	0.7	5.8
	Branches (30%)	2.96	4.23	0.70	Heat	12.1[c]	0.8	8000	0.6	4.7
Willow (0 ha)	Chips (30%)	8.16	11.66	1.00	Heat	12.1[c]	0.8	31,500	0.0	18.7
					or Electricity		0.3	11,800	0.0	7.0
Miscanthus (0 ha)	Bale (25%)	9.71	12.95	0.83	Heat	12.6[c]	0.8	30,000	0.0	17.9
					or Electricity		0.3	11,300	0.0	6.7
Softwood (0 ha)	Timber (30%)	5.77	8.24	0.70	Timber	12.4[c]	1.0	19,900	0.0	11.8
					or Heat		0.8	15,900	0.0	9.4
	Branches (30%)	1.20	1.71	0.70	Heat	12.4[c]	0.8	3300	0.0	2.0

[a] Energy yields are based on the indicated moisture content.
[b] Metabolisable energy as described by Noblet et al. [41].
[c] Kaltschmitt et al. [21].
[d] Fehrenbach et al. [42].
[e] McDonald et al. [43]: metabolisable energy for a ruminant, corrected for moisture content.
[f] Bonnadeaux [44].

2.7. Crop and tree yields

The map of land use in 2009, illustrated in Fig. 1b, was used to derive the area planted to arable crops, grassland and woodland. For the purpose of this analysis, all of the woodland was assumed to consist of hardwood species. The arable land was assumed to be planted with one of four species: winter wheat, winter barley, winter oilseed rape, and field beans as a representative spring crop. Soils data from the National Soil Resources Institute were also used to derive the soil type (coarse, medium, fine) and soil depth (100–150 cm) across the study area. A digital terrain map was also used to determine aspect and thereby the amount of solar radiation that a site would receive relative to a horizontal area. Using the soils data and a climate series of daily solar radiation, temperature and rainfall data from the area, estimates of the yield (dry matter basis) was made for each crop type using the daily time-step Yield-SAFE model [35]. Because the effect of aspect on yield was minimal, it was not considered in the full analysis. The dry matter yield for each crop, as calculated for a fine (e.g. clay) soil of 150 cm depth, is presented in Table 11. Although not used in the analysis reported in this paper, the Yield-SAFE model was also parameterised to give estimates of an equivalent annual yield from short rotation willow coppice, miscanthus, and softwood woodland. The estimated dry matter yield of 9.7 t ha^{-1} for miscanthus is similar to the mean dry matter yield of 9.6 t ha^{-1} reported by Richter et al. [36]. The dry matter yield of 8.2 t ha^{-1} for willow short rotation coppice (SRC) is broadly similar to the mean dry matter yield of 9.0 t ha^{-1} reported over two rotations from the UK SRC field trial network by Aylott et al. [37]. Typical moisture contents of arable crops, grass and wood, as reported in Table 11, were also derived from the literature to allow the calculation of a yield on a fresh weight basis. In each case, it was assumed that all of the grain, oilseed, or pulse component of each crop would be harvested. However the proportion of straw that could be harvested from wheat, barley, oilseed and beans was assumed to be 65%. The remaining 35% would remain as stubble in the field.

The proportion of the total weight of the wheat grain that could be used to produce ethanol (29%) and distiller grains (10% moisture content) (47%) were derived from Mortimer et al. [38]. Estimates of the proportion of the weight of the rapeseed crop that could be used to produce biodiesel (35%) and rapemeal (55%) were derived from Mortimer et al. [39]. The proportion of above-ground tree biomass harvested as timber and branches harvested was derived from values cited by Norman et al. [40].

The net calorific value of crop and tree products at a specified moisture content ($H_{u(w)}$; MJ kg^{-1}) depends on their calorific content when dry ($H_{u(wf)}$; MJ kg^{-1}) and their moisture content (w; %) (Eq. (1)) [45].

$$H_{u(w)} = \frac{[H_{u(wf)}(100 - w) - 2.44w]}{100} \quad (1)$$

Values of the net calorific content of crop and tree products when dry were largely derived from Kaltschmitt et al. [21] and Fehrenbach et al. [42], and corrected for the specified moisture content using Equation 1. The calorific value of crops as human feed or animal feed is typically expressed in terms of their metabolisable energy. These values were largely derived from Noblet et al. [41] and McDonald et al. [43] corrected for the stated moisture content (Table 11). The proportion of the energy that can be obtained from a biomass source also depends on the conversion process. For this analysis it was assumed that heat could be obtained at a conversion efficiency of 80% and electricity could be obtained at a conversion efficiency of 30%.

Table 12
Description of the three energy scenarios.

Scenario	Description
1.	Default position: use current cropping pattern and no bio-energy production, but described potential levels of other forms of renewable energy
2.	Use current cropping pattern, but use all food crops to provide heat and fuel, once demand for human food (but not animal feed) is met. The non-timber branchwood from woodland would also be used for heat. Assume potential levels of non-biomass renewables.
3.	Planting the whole arable and grassland area to wheat, and using that to generate heat and transport fuel, once the demand for human food (but not animal feed) is met. Branchwood is again used for heat. Assume potential levels of non-biomass renewables.

2.8. Establishing three energy scenarios

In order to examine the main interactions between the supply of renewable energy, food, feed and wood, three scenarios were proposed (Table 12). Scenario 1, a base-line scenario assuming consented development, sought to maximise renewable energy from non-biomass sources whilst maintaining current production of food, feed and wood. Scenario 2 includes the same non-biomass renewable energy sources as scenario 1, but although crop areas were assumed to remain the same, wheat and oilseed surplus to human food consumption were allocated to the production of transport fuel and animal feed, and the harvested straw of all crops was used for heat. Use of non-timber wood as a heating fuel was also assumed. Scenario 3 focused on growing wheat, a particularly high yielding crop, on the whole arable and grassland area. It was assumed that once the human crop food requirement was met, all of the additional wheat grain would be converted to bio-ethanol and all of the harvestable straw would be used for heat.

3. Results

As described in the methodology, three scenarios were used to illustrate possible trade-offs and synergies between the different sources of renewable energy, and food, feed and wood production.

3.1. Scenario 1: Renewables without bioenergy

The first scenario assumed that biomass would be used as food for humans, feed for animals (barley grain, barley straw, rape-meal, pulses, grass), and wood for timber. The 2020 target renewable electricity supply (4.6 kWh p^{-1} d^{-1}) could be met with photovoltaic panels on 12.5% of all roofing, seven commercial wind turbines, and energy from waste (Fig. 3a). If 98 commercial wind turbines were installed, then potential electricity supply would be 24.2 kWh p^{-1} d^{-1} (Fig. 3b). Renewable heating targets (3.7 kWh p^{-1} d^{-1}) could be met if ground-source heating systems were installed with all new buildings. Current human food supply was predicted to exceed demand due to the high production of wheat grain (Fig. 3). In practice much of this wheat might be allocated to animal feed, primarily for pigs and poultry. There would be a short-fall in wood supply and no supply of (transport) biofuel.

3.2. Scenario 2: Current cropping and bioenergy

Assuming current cropping practice and allocating 1.9 kWh p^{-1} d^{-1} of wheat for human food, the oilseed rape and remaining wheat could be used to produce 4.9 kWh p^{-1} d^{-1} of transport fuel. This represents 14% of current transport fuel consumption and exceeds the 10% target of 3.4 kWh p^{-1} d^{-1}. Bioethanol production from wheat produces distiller's grains, and

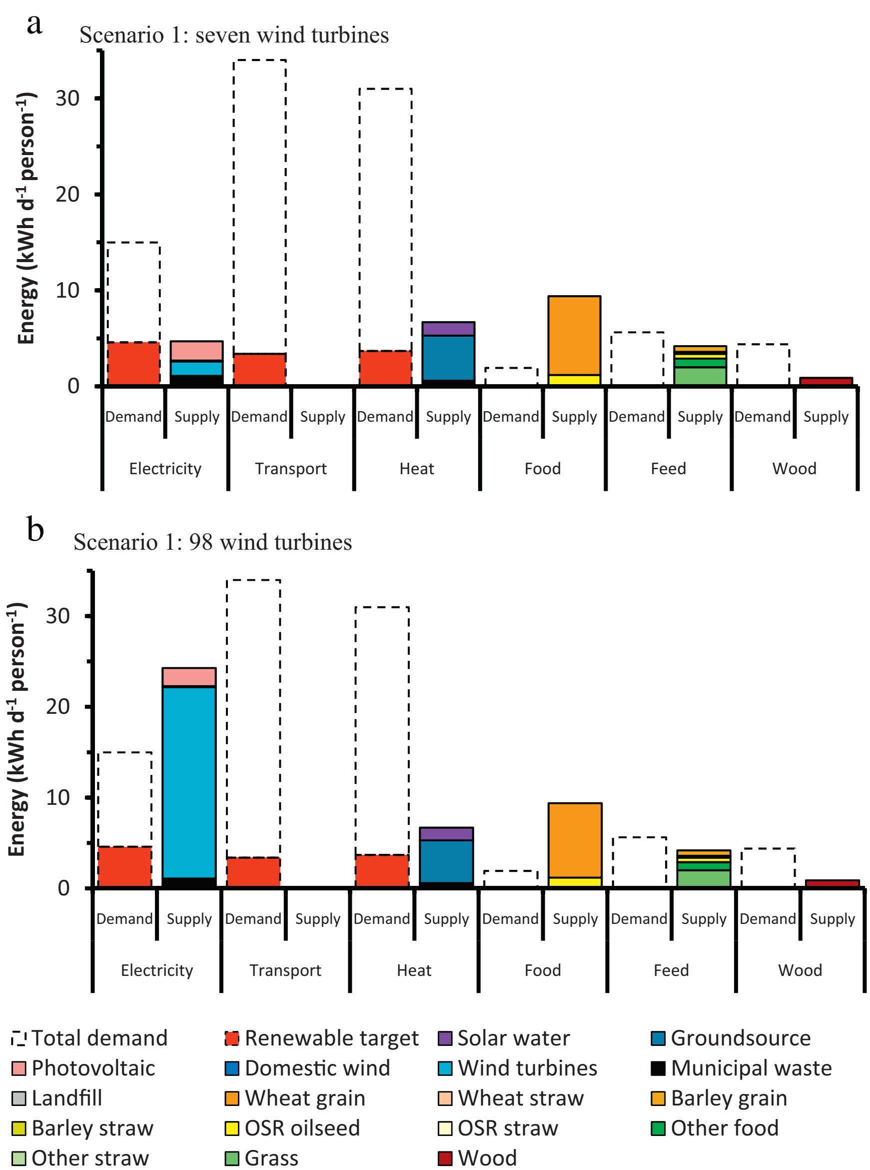


Fig. 3. *Scenario 1*: comparison of the anticipated renewable energy targets for 2020 (red) and the total demand (dotted outline) for energy, food, feed and wood, with the possible supply assuming no use of biomass or landfill for renewable energy and assuming (a) 7 wind turbines and (b) 98 wind turbines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

biodiesel from oilseed rape results in rapemeal which can both be used as an animal feed. It is assumed that all of the straw from wheat, barley, oilseed rape, and other crops was used exclusively for heating (5.9 kWh p^{-1} d^{-1}), plus 0.6 kWh p^{-1} d^{-1} from branches used as woodfuel (Fig. 4a).

3.3. *Scenario 3: Monoculture wheat for maximum biofuel*

Within the Vale, wheat is one of the highest yielding crops. Scenario 3 assumed a change in current land use to planting wheat on all arable and grassland areas. The levels of renewable energy from

Table 13
Effects of three scenarios on the supply of electricity, transport fuel, heat, food, feed and wood (kWh p^{-1} d^{-1}).

Form of demand	Total demand	Renewable targets	Scenario			
			1a. No biomass renewables + 7 wind turbines	1b. No biomass renewables + 98 wind turbines	2. Current cropping with renewables	3. Monoculture wheat with renewables
Electricity	15.0	4.6	4.7	24.3	24.3	24.3
Transport	34.0	3.4	0.0	0.0	4.9	11.4
Heat	31.0	3.7	6.1	6.1	12.6	15.7
Food	1.9		9.4	9.4	1.9	1.9
Feed	5.6		4.2	4.2	7.2	9.9
Wood	4.4		0.9	0.9	0.9	0.9

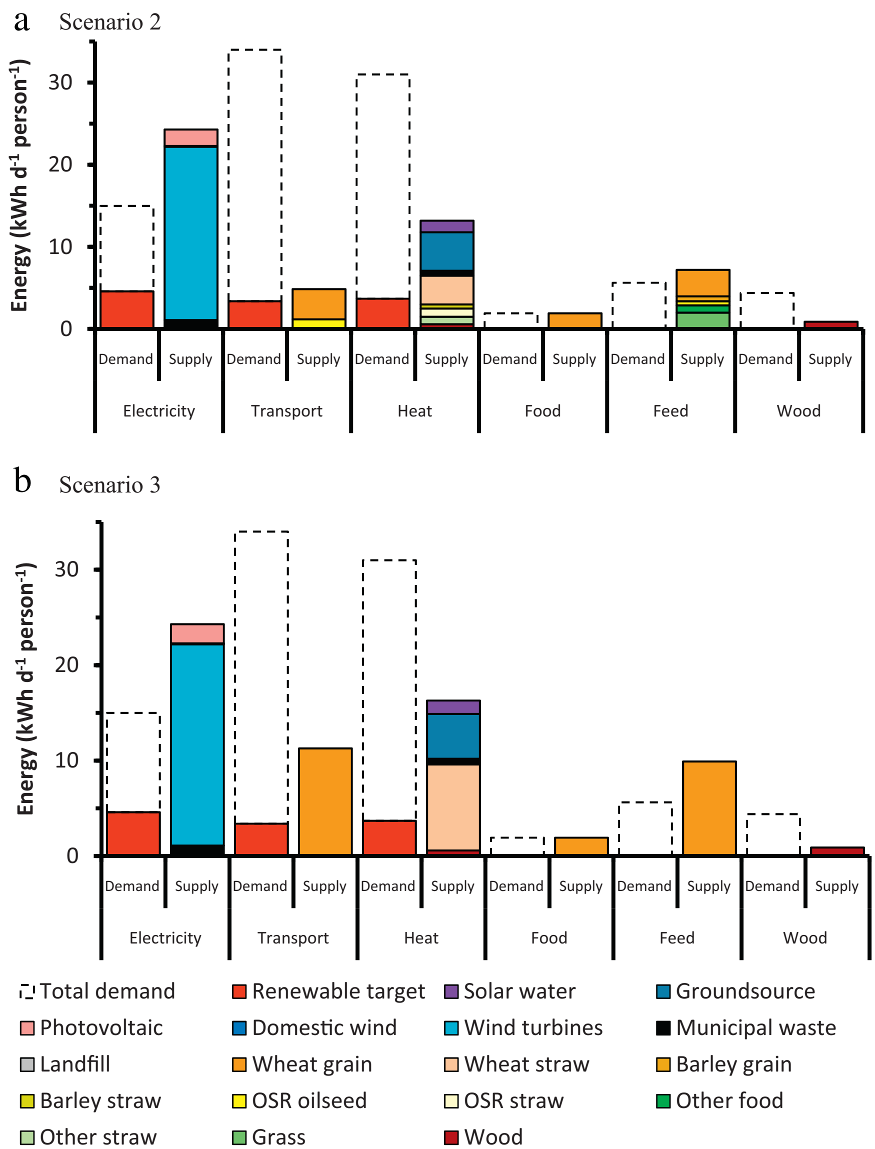


Fig. 4. Comparison of renewable energy targets for 2020 (red) and the total demand (dotted outline) for energy, food, feed and wood with the predicted supply, assuming (a) *Scenario 2* where current land use is maintained but all wheat grain and oilseed is used for the production of transport fuel (once human crop food requirements are met), and (b) *Scenario 3* where wheat is planted on all agricultural areas. In each case, all straw and branches are used for heating, and distillers grains from the wheat and rapemeal from the oilseed is used as animal feed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

wind, solar photovoltaics, municipal waste, solar water heating, ground source, and water source heating are the same as in Fig. 3b. It was anticipated that transport fuel production (bio-ethanol) could reach 11.3 kWh p^{-1} d^{-1} (33% of current demand). Assuming that all of the harvestable wheat straw was used for heating, the heat supply could reach 16.3 kWh p^{-1} d^{-1} (53% of total demand) (Fig. 4b).

4. Discussion

4.1. A framework to promote discussion

In recent years, the ongoing energy debate in the UK has helped members of the public to formulate their opinion on energy futures at the national level, e.g. there is now a very strong public support for renewable energy *in principle*. However as long as the local level consequences of national preferences are not well understood, national opinion polls will remain a poor basis for strategic planning and policy implementation on the ground [58]. The analysis presented in this paper helps to visualise the changes in low carbon energy demand and supply that are required at local or regional levels. The energy unit used in this paper is energy demand and supply per person. In promoting discussions with local stakeholders, this approach has proved useful by creating a tangible “human-sized” measure which provides scope for a locally grounded and equity-based discussion. It also allows individuals within a local area to examine if, given their level of energy, food and wood consumption and the renewable energy potential of their area, they are doing or accepting ‘their bit’ with respect to the uptake of renewable energy. Within this analysis we have used the units of kWh p^{-1} d^{-1}. Although kWh is not a standard SI unit, it is the unit by which people in the UK pay for electricity and gas. It may prove useful, in terms of improving energy literacy and for ease of comparison, if in the future petrol and diesel prices could also be expressed in terms of kWh. Similarly it would be useful if new vehicles were able to indicate their fuel use in terms of kWh in addition to miles per gallon or kilometres per litre. The recognition of such a unit will also become greater with the introduction of electric vehicles.

4.2. Reducing the demand for energy

A useful feature of the framework used in this paper, is that the demand for energy, food, feed and wood is described in absolute terms against the potential local supply. Current targets such as achieving a certain proportion of energy supply can draw one's focus away from the possibility of reducing demand as a method of achieving a balance between demand and supply. As illustrated in Table 4, in 2009 per capita energy use in the UK was equivalent to about 80 kWh p^{-1} d^{-1}. The UK government has predicted [2] that UK energy use should be 144,100 ktonnes of oil equivalent in 2020. Because the UK population is predicted to increase (+8%) from 61.4 million in 2008 to about 66.9 million in 2021 [46], the prediction for 2020 is equivalent to a per capita energy use of 68 kWh d^{-1}. This is the same value that MacKay [9] proposed would be possible for 2050. Reaching this value will require a 20% reduction in energy use per person over the next nine years. This can partly be achieved by reducing the demand for heating (which accounts for about a third of UK energy use) for example through roof, window and wall insulation. Other options include improvements in lighting efficiency, improved building energy management systems, and new regulations for new buildings [47]. However it is important to realise that the above value relates only to energy use within the UK. It does not include the embedded energy of items produced in other countries which are then imported into the UK [48]. Whilst moving energy intensive processes outside of the UK is one method of reducing UK energy consumption, it does not reduce energy consumption at a global level. With this qualification, the framework presented in this paper provides a mechanism by which options which reduce energy demand can be compared directly with options to increase supply.

4.3. Reducing the demand for food and feed

The framework also provides a per-capita estimate of the demand for food and animal feed. Two key areas for reducing these are reducing food waste and reducing the consumption of animal-based products. The values used to derive the requirement for human food (Table 5) assumed a 10% level of waste [15]. However WRAP [49] suggest that the proportion of the total weight of food wasted at a household level is 22% of which 63% (14% of the total weight) is avoidable. Changes in behaviour and new technologies that can reduce food waste are obviously important. The results presented in Table 5 suggest that delivering our food energy requirements in terms of animal products typically requires about 7.8 kWh of plant product energy for every 1 kWh of animal product energy. Hence initiatives to (i) improve the efficiency of animal production, and (ii) reduce the demand for meat and milk-based products could substantially reduce the demand for animal feed.

4.4. Level of wood self-sufficiency

The proportion of the land area covered by wood in the Marston Vale (8%) is about 68% of the UK average (11.7%). Even so, assuming typical rates of annual wood production per hectare, the analysis showed that the Marston Vale was only able to supply 22% of its wood requirements. The framework therefore highlights the low level of self-sufficiency and the dominance of imported wood within the UK. In 2005, the UK imported about 68% of the wood (sawnwood, wood-based panels, paper and paperboard) that it consumed [19]. Because about 60% of the consumption was related to paper manufacture, reduced and more efficient use of paper could produce significant benefits.

4.5. Relative magnitude of the demand for energy and food

Describing energy and food on a common scale highlights that the demand for delivered energy (currently 80 kWh d^{-1} p^{-1}) is an order of magnitude greater than our demand for food and feed (7.5 kWh d^{-1} p^{-1}). It is also six-times greater than the current supply of food and feed (13.6 kWh d^{-1} p^{-1}) from the Marston Vale, which has a population density midway between that for the UK and England (Table 13). This difference highlights the major limitations in using biomass production within the UK to address issues of energy security particularly when high food prices are a concern for many. Even if the total arable and grassland area was planted to a highly productive crop like wheat, the Marston Vale could only supply 11 kWh d^{-1} p^{-1} (33%) of the current demand for transport fuel, and 16 kWh d^{-1} p^{-1} (53%) of the demand for heat energy. Moreover this is only achievable by annually using all of the harvested straw for heating, and in the medium- to long-term this will lead to reduced soil organic matter levels and reduced yields.

4.6. Forms of energy

The analysis has considered energy in the form of electricity, transport fuel and heat. Each form has different properties in terms of its storage, transport and thermodynamic 'quality' [50]. The chemical energy embedded in fuels is considered to have a high thermodynamic quality and it can be stored until required. Electricity also has a high thermodynamic quality but it is currently difficult to store; conversely heat energy is considered to have a low thermodynamic quality and whilst it can be stored for a short period of time (e.g. in insulated hot water tanks), it is difficult to transport. However where it can be used, the efficiency of obtaining heat from a fuel (80%) is substantially higher than that for electricity (30%). In practice it is possible to use a combined heat and power (CHP) plant to use the heat at the same time as generating electricity. However the success of such systems typically requires enterprises close to the power-plant which can benefit from a year-round supply of heat.

4.7. Difficulty in producing transport fuel

Scenario 3 shows that the Marston Vale (with a population density of 3.1 people ha^{-1}) could only supply 33% of the current demand for transport fuel (34 kWh p^{-1} d^{-1}), even if all of the arable and grassland area was planted to wheat. By contrast, assuming a high level of wind turbines or the short- to medium-term production of electricity from landfill gas, there appears to be potential to increase renewable electricity production. This analysis would support the observation made by others [9] that transport will have to become increasingly electricity-based within a low carbon economy.

4.8. Electricity generation

The calculations show that within the Marston Vale, wind seems to offer the greatest potential for renewable electricity generation. Although there would be landscape impacts, the construction of 98 wind turbines, which would cover about 7% of the area, was estimated to produce the equivalent of 21 kWh p^{-1} d^{-1}. This is similar to the value of 20 kWh p^{-1} d^{-1}, calculated by MacKay [9] for onshore wind turbines covering 10% of the UK. In this analysis we have only focussed on terrestrial sources, but many studies have also placed emphasis on off-shore wind. For example the Centre for Alternative Technology [51] in their Zero Carbon Britain 2020 scenario assumed that 52% of the indigenous UK energy production would come from off-shore wind. However even with a country-wide network, the temporal variability in wind speeds means that

alternative methods of producing electricity, storing energy and managing energy demand are still required.

The assumed annual electrical energy yield from solar photovoltaics of 117 kWh m^{-2} appears to be at the top end of outputs reported from currently installed systems. For example Tovey and Turner [52] report an output of 74 kWh m^{-2} for a roof-mounted mono-crystalline system in Eastern England. Our analysis shows the limited potential of solar photovoltaics (1.6 kWh p^{-1} d^{-1}) if they are limited to only one-eighth of the area of domestic housing (5 m^2 of panel per person). MacKay [9] proposed a potential output from photovoltaics of 5 kWh p^{-1} d^{-1}, but this was based on the equivalent of 10 m^2 of photovoltaic panels per person. Although not considered in this paper, there is also the potential possibility of the creation of solar farms.

4.9. Heating

The value estimated for solar water heating (1.4 kWh d^{-1}) from a 1 m^2 panel is similar to the value of 3.8 kWh d^{-1} for a 3 m^2 panel reported by MacKay [9]. However whereas we have assumed only 1 m^2 of solar heating panel per person, MacKay assumed that each person could install 10 m^2 of panels (13 kWh p^{-1} d^{-1}). The lower estimate presented here seems to be closer to the current practice of installing systems that match water heating requirements during the summer. Because of the difficulty in installing ground-source heating in existing buildings, ground-source heating was only assumed in new properties. In an area such as the Marston Vale where substantial levels of new housing are planned, such heating could be significant (6.5 kWh p^{-1} d^{-1}) (Table 8). However this output also requires an electrical input for pumping equivalent to 1.8 kWh p^{-1} d^{-1}. In order to maximise the energy gains from the system, it is desirable that the electricity used to drive the pump is derived from a non-biomass source.

4.10. Landfill energy

In the three scenarios, energy derived from landfill gas was ignored. Landfill in the Marston Vale is currently assumed to be contributing electricity equivalent to 14 kWh p^{-1} d^{-1}; at present there is minimal use of the heat generated. Assuming that it was possible to use the landfill gas for combined heat and power generation (e.g. by running low-pressure gas pipes from the landfill site to built up areas), then the landfill gas could generate about 23 kWh p^{-1} d^{-1}. Over the short-term this could be a very significant energy source equivalent to nearly all of the predicted local demand for electricity and most of the heat. However over the long-term the energy produced will decrease as landfill gas yields decline, though the rate the rate of the reduction is difficult to determine. Although landfill gas is an important source of renewable energy in the UK, its particular prominence in the study area is untypical for the UK as a whole, being a result of local clay geology, the availability of large pits associated with brick manufacturing, and proximity to large population centres such as London.

4.11. Greenhouse gas savings

The presumption in this paper is that the renewable energies described result in lower net greenhouse gas emissions than the extraction and use of fossil fuels. Even amongst fossil fuels, the amount of carbon dioxide emitted per energy output depends on both the fuel source and the type of energy delivered [50]. For example the supply of 1 kWh of electricity results in 882 g CO_2 if produced from coal and 376 g CO_2 if produced from gas [53]. These are similar to values of 945 and 424 g CO_2 kWh^{-1} for electricity production from coal and gas respectively as reported by Cannell [54]. Assuming that the carbon contained in the biomass would not have been sequestered in the absence of harvesting that crop, then the predicted emission from an electrical power plant using biomass has been estimated to be 44 g CO_2 kWh^{-1} [54]. This may be the case for sustainable biomass removal from a mature forest. However in other situations the harvesting of biomass may simply reduce the natural sequestration of carbon.

The extraction and use of petrol and diesel have been estimated to result in the emission of 293–315 g CO_2 equivalent kWh^{-1} [55]. By contrast net greenhouse emissions for the production of bioethanol from wheat range from 42 to 228 g CO_2 equivalent kWh^{-1}, and that for biodiesel from oilseed rape ranges from −20 to 166 g CO_2 equivalent kWh^{-1} [55]. These values represent net greenhouse gas savings of between 22 and 106% depending on the use of the co-products, soil type, and previous land use. Converting arable land to perennial crops such as woodland, short rotation coppice, miscanthus or grass, is usually beneficial in reducing the oxidation of soil carbon [56]. By contrast, converting grasslands and forests into cultivated arable land will reduce the net greenhouse gas emission benefits. The reduction of soil carbon caused by removing straw, rather than incorporating into the soil, will also create environmental costs if straw is used as an energy source. The scenarios described in this paper need to be analysed further to predict their effect on net greenhouse gas emissions.

4.12. Ecosystem services

Effects of renewable energy supply on ecosystem services go beyond the three provisioning services of food, feed and wood considered here. Increased biomass fuel production from perennial crops can lead to increased competition for water supply, whilst having positive effects on water quality. There are also effects on other ecosystem services such as carbon sequestration, habitat creation, and cultural services including recreational opportunities which will be explored in future papers from this project. These and the interactions reported here need to be better understood to ensure appropriate assessment of the environmental impact of land use decisions [57].

5. Conclusions

Energy policy was traditionally set at the national level, whilst energy consumption was studied for individual households. The framework used in this paper enables the development of energy scenarios at any intermediate geographical scale between the national level and the household level, linking local production potential with the local level of consumption, and exploring the synergies and trade-offs between local renewable energy production on the one hand and the production of other land-based commodities on the other. By expressing the demand and supply of energy (electricity, transport and heat), food, animal feed and wood in a common per capita unit, this framework can be used to examine how a range of national policies – on energy, housing, agriculture, land use – could be implemented in a balanced and integrated way at the local level. The development of scenarios to explore what can be done locally, can help to inform local planning decisions and facilitate public engagement in the (otherwise rather abstract) energy debate on a more concrete and contextualised basis. To the extent that the population density in the Marston Vale is similar to that in the UK, the study also serves as a microcosm of the UK energy landscape. Finally, the framework lends itself for further extensions, e.g. to compare the options in terms of net greenhouse gas emissions, finance, and public perceptions.

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